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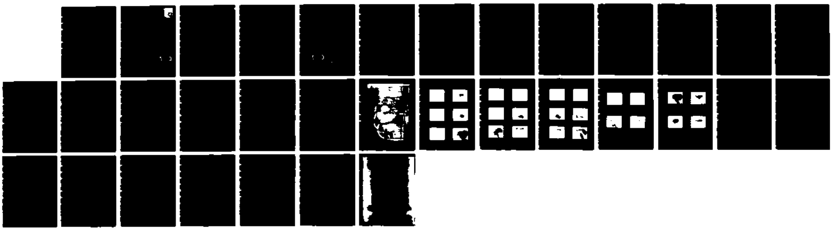

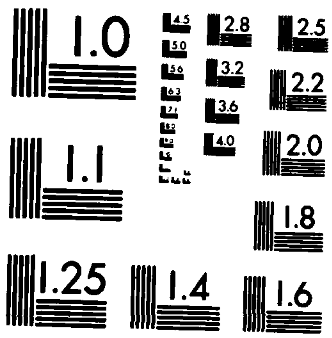

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AN EXPERIMENTAL AND THEORETICAL INVESTIGATION OF AN NEMP TYPE FAST RISE LIGHTNING SIMULATOR

J. D. Robb
Lightning & Transients Research Institute
2531 West Summer Street
St. Paul, MN 55113

3-15-1984

Final Report for Period July 1982 - March 1983

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This technical report has been reviewed and is approved for publication.

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Recent lightning phenomena investigations have indicated lightning currents for the high current return phase of lightning strikes to ground of 100 nanoseconds, an order of magnitude faster than the previously accepted value of one to two microseconds. An experimental investigation was undertaken to evaluate the feasibility of using NEMP type generators to provide the faster rise times for lightning testing of aircraft. The program consisted of (a), a theoretical phase to examine the required generator parameters, (b) a low level 300 kilovolt experimental phase with a 30 foot long cylinder, six feet in diameter to represent an idealized aircraft under test and (c), a final phase in which a design was developed for testing of full size aircraft at the test current level of 40,000 amperes.

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FOREWORD

This report, L&T No. 765, is the final report covering the studies of NEMP type generators for lightning testing of aircraft.

LTRI personnel participating in this report's studies and report preparation included J. D. Robb, B. A. Sventek, E. M. Stai, J. D. Anderson and T. J. O'Keefe.

Technical monitor on the contract representing the Air Force was Mr. L. Walko.

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1.0 INTRODUCTION

Recent airborne and ground based lightning investigations have indicated lightning currents for the high current return phase of lightning strikes to ground of 100 nanoseconds, which is an order of magnitude faster than the previously accepted value of one to two microseconds. An experimental investigation has been undertaken to evaluate quantitatively the feasibility of using nuclear NEMP type generators to provide the faster rise times for lightning testing of aircraft.

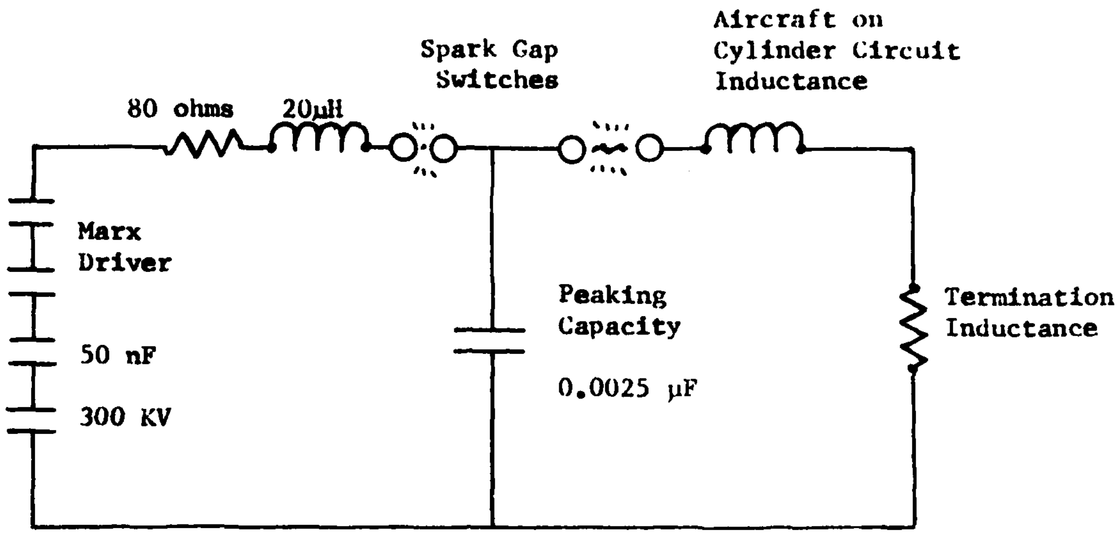
The program has consisted of a), a theoretical phase to examine the required generator parameters, b) a low level 300 kilovolt experimental phase with a 30 foot long cylinder, six feet in diameter to represent an idealized aircraft under test and c) a final phase in which a design is developed for testing of full size aircraft at the test current level of 40,000 amperes. This represents an above average lightning strike. The theoretical analysis was carried out under a subcontract with Electro Magnetic Applications, Inc. (EMA) of Denver.

2.0 BASIC CONCEPT

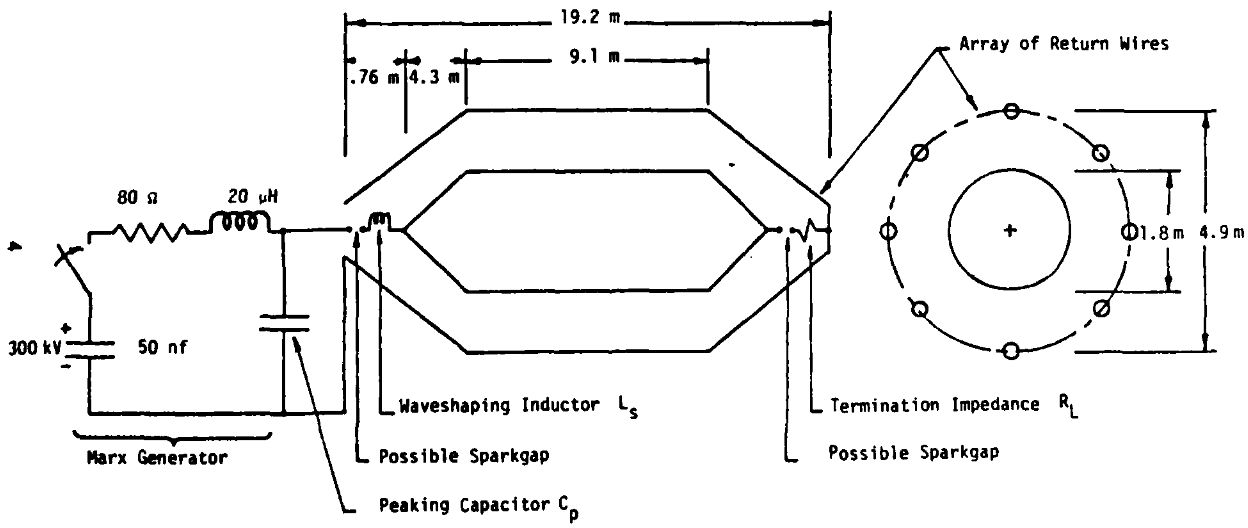
The nuclear electromagnetic pulse simulator (NEMP) basic circuit is illustrated in Figure 1a. An initial generator, usually of the Marx impulse type, supplies high voltage of the order of one to four megavolts which is fired into a low inductance peaking capacitor circuit which in turn, after it is charged, fires successively into the load circuit. The load circuit in the case of the NEMP systems, is a parallel plate transmission line for applying electromagnetic fields to the vehicle under test. In this study, the generator is fired into the actual vehicle in order to inject lightning level currents and test the vehicle for vulnerability to lightning damage and circuit upset. The vehicle for the first low level phase of the investigation was a metal cylinder used for the purpose of representing an idealized aircraft which could be more easily analyzed theoretically. The test arrangement is illustrated in Figures 1b and 1c.

Whereas the high voltage Marx generators currently in use have large inductances which limit the current rise times to one to two microseconds, the high voltage peaking capacitors can be designed with very low inductance to provide rise times of the order of ten nanoseconds as required for NEMP applications.

The basic decision in the design of such a system, is to determine the rise time needed to simulate the in-flight environment. The faster the rise time in general, the more expensive the peaking capacitors. However, none of the data to date indicates rise times of faster than about 30 to 50 nanoseconds which requires much less expense in the construction of the system and the peaking capacitors, than does the ten nanosecond risetimes required for NEMP testing.



(a)



(b)

Figure 1 Equivalent Circuit Diagram, Above, and Simplied Sketch, Below of Cylinder Test Arrangement

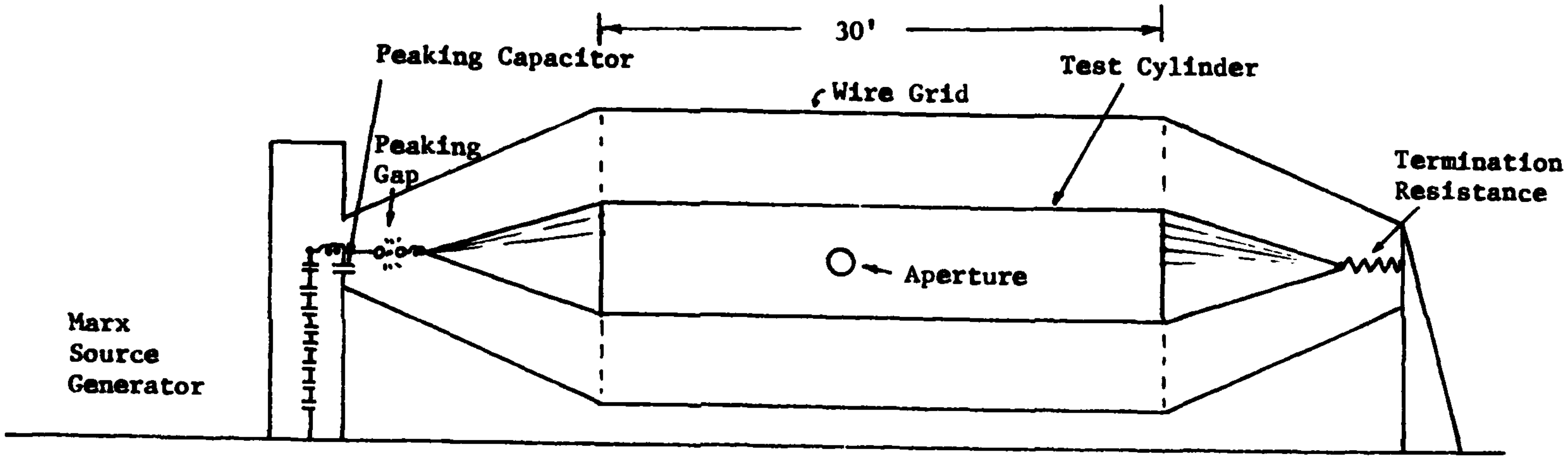


Figure 1c. Cylinder Test Arrangement Approximately to Scale.

The output waveform of such a system is shown in Figure 2a. It consists essentially of two double exponential waveforms superimposed, one from the Marx generator supplying the long pulse and a second from the peaking circuit for supplying the fast initial pulse. There can be a dip before reaching the second crest of the Marx generator output current.

As shown in the figure, the idealized waveform would be a true double exponential with a very fast 100 nanosecond rise time and the long 50 microsecond tail. The cost trade off lies essentially in the size of the peaking capacitor to supply the initial front of wave with minimum dip, as illustrated in Figure 2b. The smaller and more economical the peaking capacitor, the greater the dip and the less closely the output wave form approaches the desired double exponential.

Two basic studies were carried out:

(a) A theoretical and experimental analysis of a six foot diameter by thirty foot long cylinder excited by an NEMP type generator. It was used in the experimental studies to represent an idealized aircraft which can be analyzed theoretically for better correlation with experimental studies. The theoretical studies were carried out by EMA.

(b) A design study for a full scale four megavolt NEMP system to test the full size aircraft, the design of which would be based on the experimental study of the cylinder by LTRI and a companion theoretical study carried out by EMA.

3.0 - BASELINE PARAMETERS

The baseline parameters as determined from the preliminary studies under the contract by EMA are summarized in Table 1. They include:

(a) The number of wires to be used in the return grid for the system. The greater the number of wires the lower the impedance of the system but with diminishing returns as the wire number increases.

(b) The spacing of the wires from the idealized cylinder or aircraft.

(c) The capacity of the peaking capacitor.

(d) The capacity of the Marx generator.

(e) The resultant surge impedance of the system and the termination resistor to be used at the far end.

(f) The effects of downstream spark gaps.

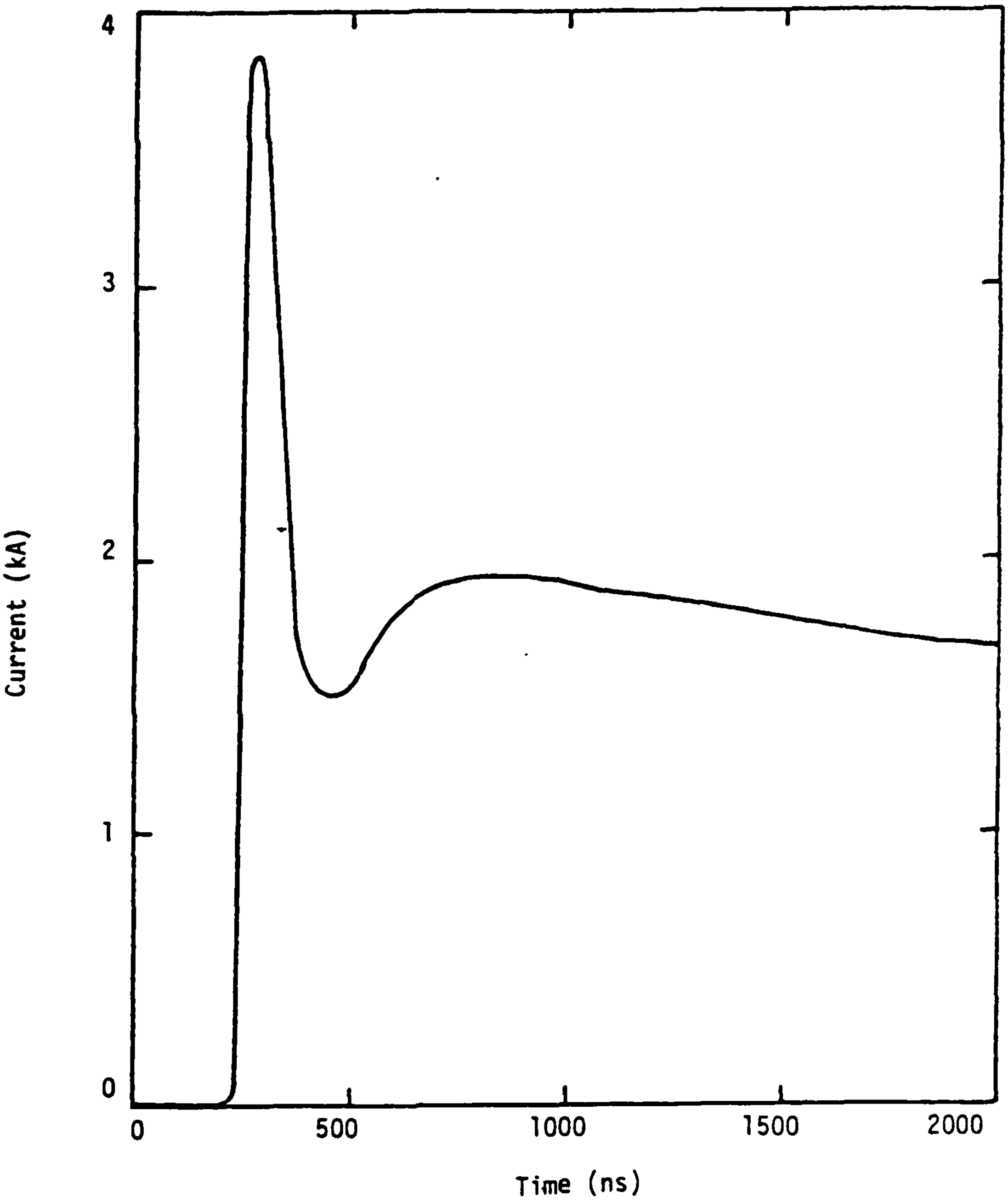


Figure 2a. Injected Current Waveform for Baseline Configuration from EMA Studies

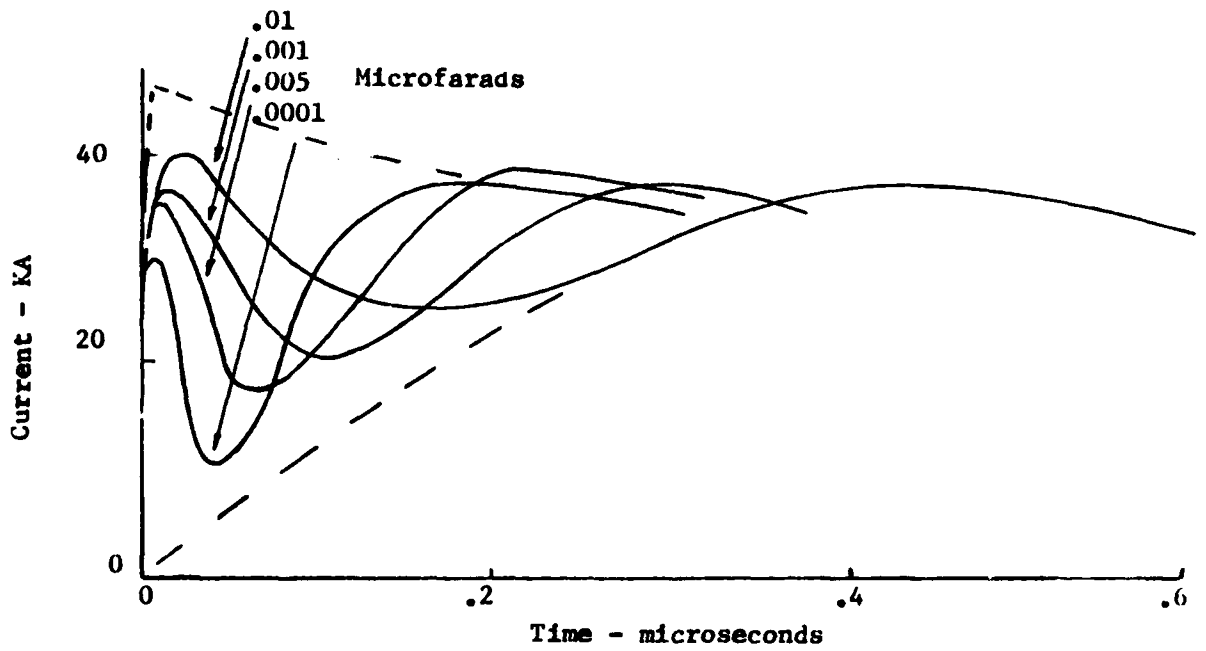


Figure 2b Variation in Waveform Dip with Change in Peaking Capacity.

TABLE 1
NEMP TYPE LIGHTNING SIMULATORS
LIST OF EVALUATED PARAMETERS

1.0 LINE PARAMETERS

1.1 Generator Orientation
Vertical, Horizontal or Angled

1.2 Cylinder and Return Wire Spacings

a. Spacings	5'	10'	15'
b. No. of Wires	8	16	32
c. Size of Wires	0.1	0.2	0.6
d. Surge Impedance - From Studies			

1.3 Rise Times	30 to 300 nanoseconds
1.4 Peaking Capacitor	.5 to 3 nanofarads
1.5 Series Inductance	3 uH to 30 uH
1.6 Termination Connection	Matched, Short, Open
1.7 Termination Impedance	70 to 150 ohms

2.0 SWITCHING NOISE — Evaluation of Level

3.0 STANDARD CONFIGURATION

	Cylinder	Aircraft
a. Spacing	5 feet	15 feet
b. Wire Size	1/8 inch	5/8th inch
c. Wire Number	16	32
d. Rise Time	125 nSec	125 nSec
e. Series Inductance	10 uHenry	10 uHenry
f. Peaking Capacitor	.003 uFarad	.001 uFarad
g. Generator Capacitor	.050 uFarad	.01 uFarad
h. Marx Generator Voltage	300 Kilovolts	4 Megavolts

As shown in the Table, selected values were used for the experimental investigation's idealized cylinder and variations of the various parameters were carried out under the analytical study to determine the resultant effects. These were confirmed with experimental measurements by LTRI on the test cylinder for the nominal case.

4.0 - RISE TIME DEFINITIONS

One problem initially encountered in the investigations was the fact that there are a number of different rise time definitions and that for the purposes of this investigation these would need to be correlated in order that there was no ambiguity in the investigation of the parameters. As shown in Figure 3a and 3b the definitions include:

(a) Rise time to be the time between the ten percent and ninety percent value of the wave crest,

(b) Time between the thirty percent and ninety percent value of the crest; and

(c) Time to peak and the rate of rise.

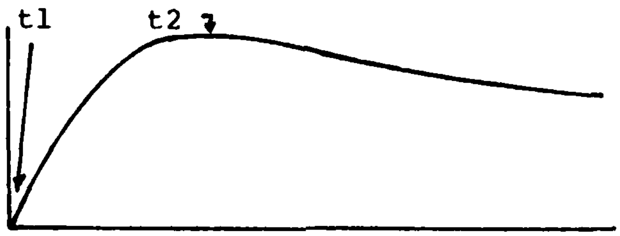
The rates of rise which are in general use are the old value of 100,000 amperes per microsecond, the new value of 200,000 amperes in current use for some applications and the 1,000,000 amperes per microsecond rise time being suggested on the basis of the current researches.

As may be seen in Figure 3b, the 100,000 ampere per microsecond rise corresponds to a time to peak of nearly eight microseconds. The 200,000 amperes per microsecond rise time corresponds to a rise time to peak of approximately half that value or four microseconds. The 1,000,000 amperes per microsecond current rate of rise corresponds to a time to peak of a little under two microseconds. Thus the older rise time of one microsecond is quite severe if defined as the time to crest but inadequate if defined as the time to the front of wave.

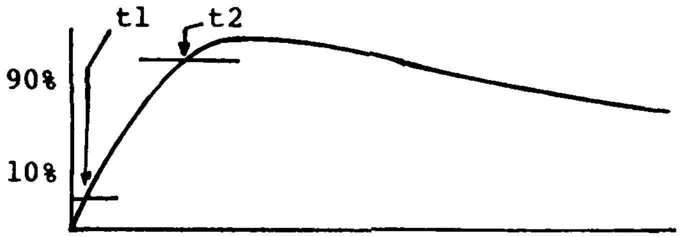
5.0 - RESULTS OF THE THEORETICAL INVESTIGATIONS BY EMA

The theoretical investigations by EMA have suggested that for the test, a fairly clean front of wave with a single initial pulse and a single slow pulse from the Marx generator can be obtained by additional inductance to the input of the vehicle. This is quite important because as has been suggested by R. A. Perala, a clean wavefront is important in order to assure that the high frequency transient signals measured on vehicle circuits are not merely a result of excitation by front of wave drive current transients or hash. With this addition the fast reflections which occur at the discontinuities of the feed line to the vehicle and between the vehicle and the termination are suppressed sufficiently that the remaining wave form is fairly clean.

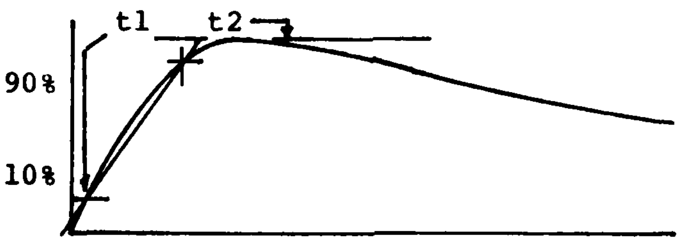
1.0 Defined as risetime from zero to crest



2.0 Defined as risetime from 10 percent to 90 percent of crest



3.0 Defined as 1.67 time risetime from 10 percent to 90 percent of crest



4.0 Defined the time from zero to 1 - 1/e

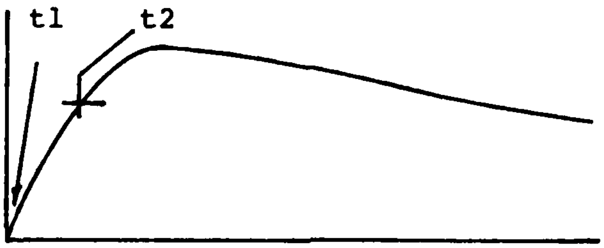


Figure 3a. Definitions of Waveform Risetimes

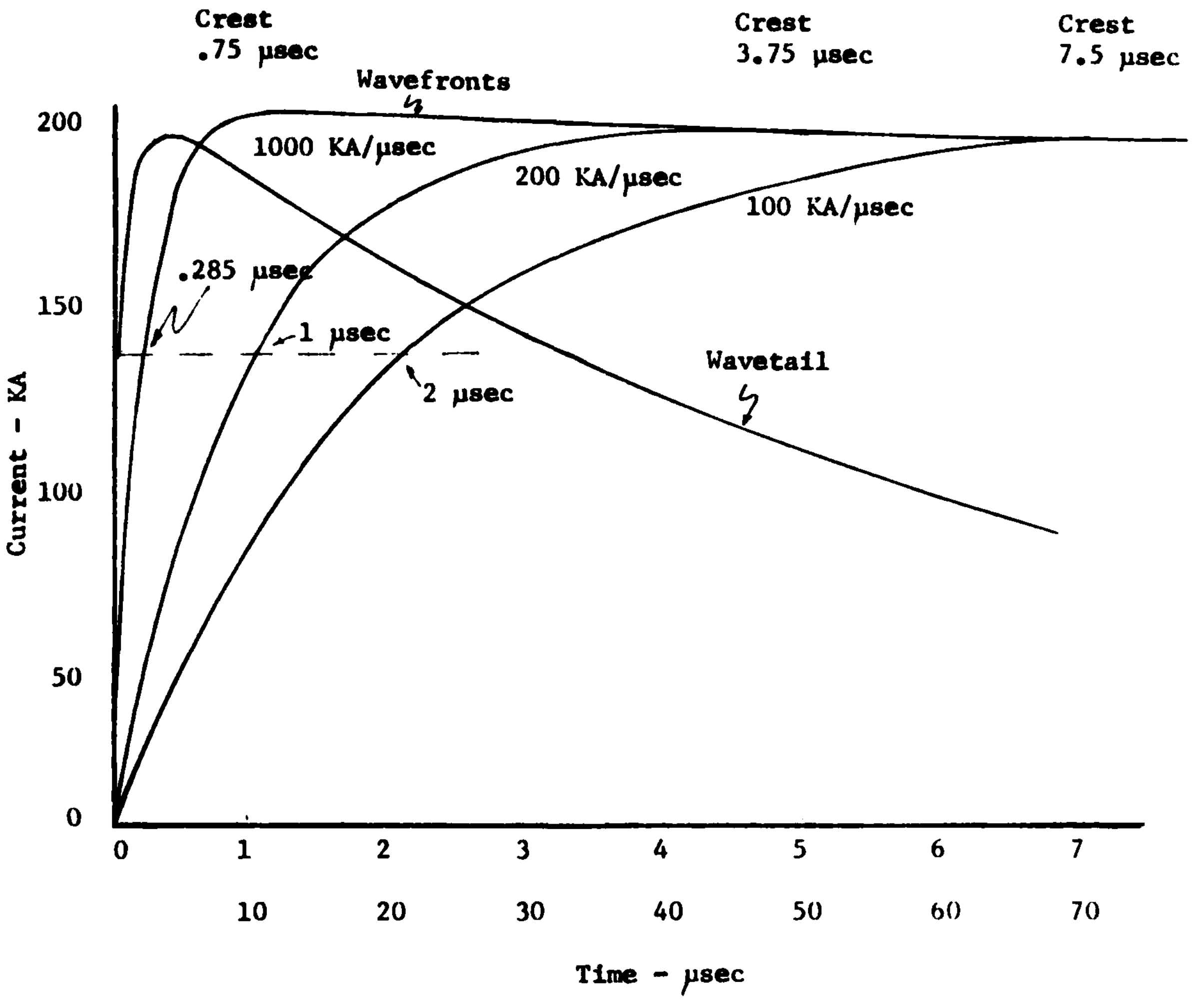


Figure 3b. Graph of Standard Waveforms in Current Use Or Proposed for Use

The oscillations between the initial pulse and the secondary Marx generator pulse can occur if sufficient peaking circuit resistance is not added and, therefore, addition of peaking capacitor resistance may be required for this purpose. This cuts down the peak voltage out of the peaking capacitor but may be worth it in terms of providing a cleaner wave form for analysis purposes.

One important point is that if inductance is being added to the input of the test vehicle to damp down the reflections and provide a cleaner front of wave, then, as noted, very expensive low inductance peaking capacitors become less necessary and a considerable economy can be effected in peaking capacitor purchases.

6.0 - Cylinder Test Arrangement

The test arrangement with the six foot diameter by thirty foot long cylinder for the experimental investigations is shown in Figure 4. To the right is shown the Marx impulse generator housing followed by an isolation inductance feeding the peaking capacitor system. Next, the output of the peaking capacitor feeds through a spark gap switch into the inductance at the input to the feed for the test cylinder. Following the test cylinder is the downstream termination resistance or downstream spark gap for applying greater E field excitation of the system. The instrumentation for measuring the parameters of the system was enclosed inside the cylinder as the interior represented a low field environment, a shielded room in effect, for measurements. Parameters measured included the input current, the radial electric field and the tangential magnetic field around the cylinder. The measurement sensors utilized included:

(a) A simple resistance shunt (current viewing resistor) for measuring the current (about 2,000 amps for 200 kV)

(b) A simple plate sensor on the inner surface of the cylinder exposed to the interior through a one inch hole for measuring the radial electric field (220 kV/m - 200 kV)

(c) A simple ten centimeter loop for measuring the tangential external magnetic field (150 A/m - 200 kV)

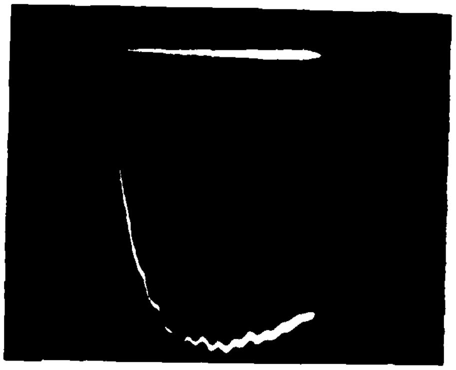
As shown in the oscillograms of Figures 5a through 5e, the current and electric field are relatively clean on the front of wave. The magnetic field does show some oscillations. The results shown are for the line open circuited, short circuited and terminated. As might be guessed, the terminated line provides the smoothest wave form.

7.0 - Noise Tests

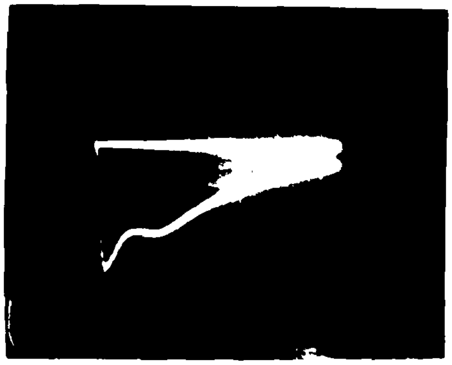
Tests were next carried out to determine the effect of the lack of shielding on the Marx generator. This was done by firing the

Figure 4. Photograph of Cylinder Test Arrangement

DRIVE CURRENT

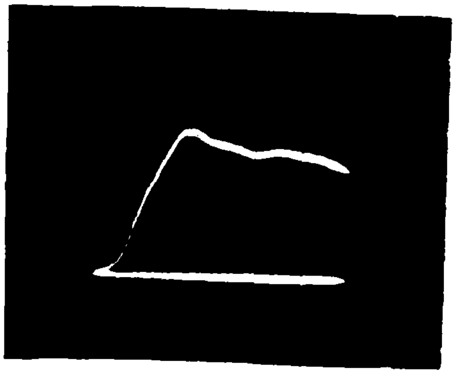


256 Amp/div 0.1 us/div

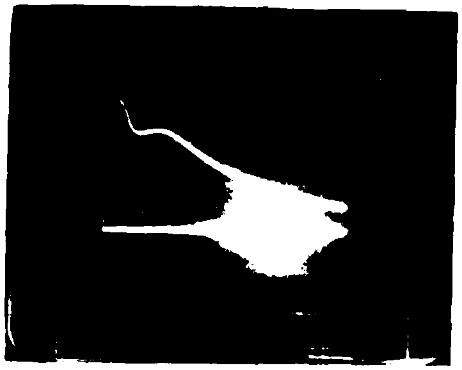


640 Amp/div 1 us/div

E-FIELD

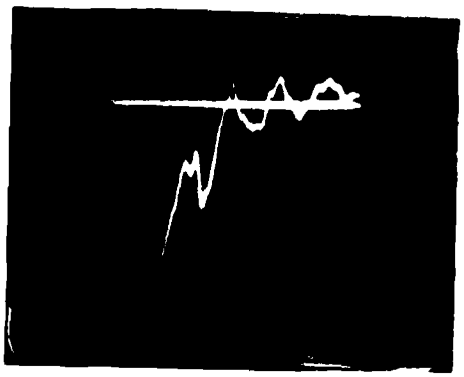


80 kV/m/div 0.1 us/div



80 kV/m/div 0.1 us/div

H-FIELD

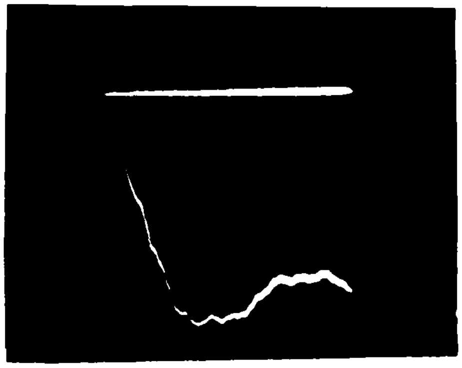


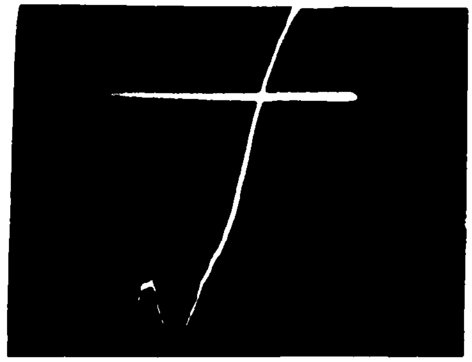
35 A/m 0.1 us/div

35 A/m 0.2 us/div

Figure 5a. Oscillograms of Cylinder with Termination

DRIVE CURRENT

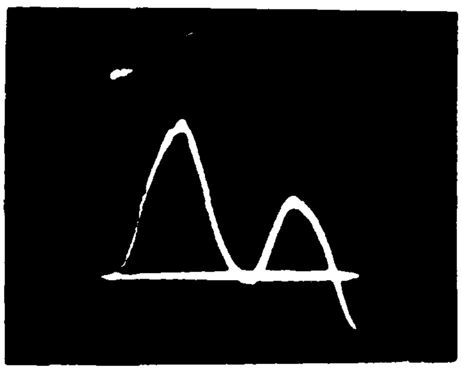


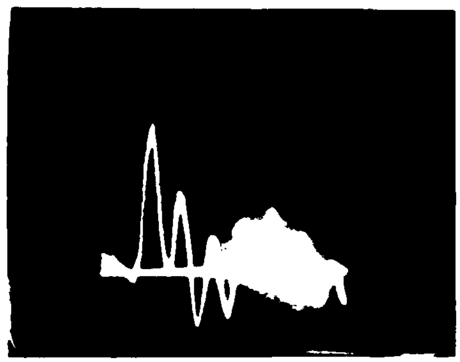


640 A/div 0.1 us/div

640 A/div 1 us/div

E-FIELD

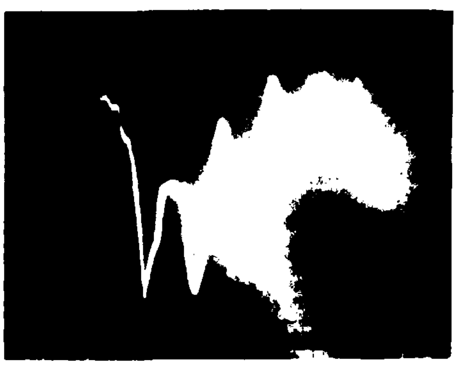


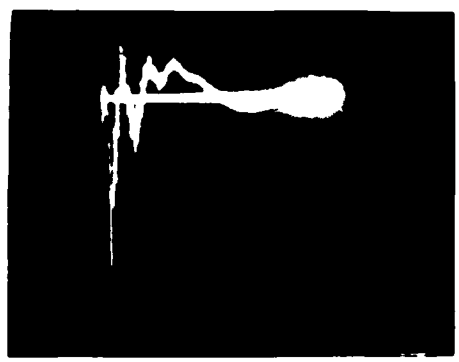


20 kV/m/div 0.1 us/div

20 kV/m/div 1 us/div

H-FIELD



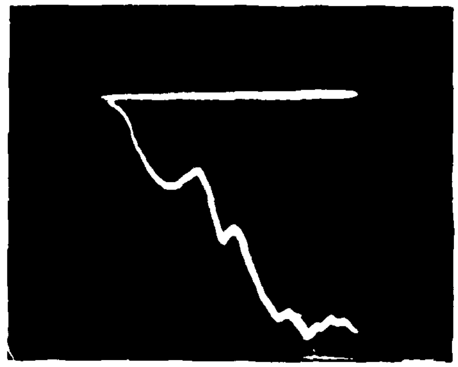


35 A/m/div 0.1 us/div

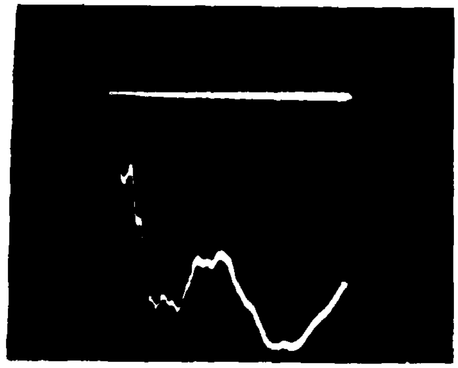
35 A/m/div 0.2 us/div

Figure 5b. Oscillograms of Cylinder with Short Circuited Termination.

DRIVE CURRENT

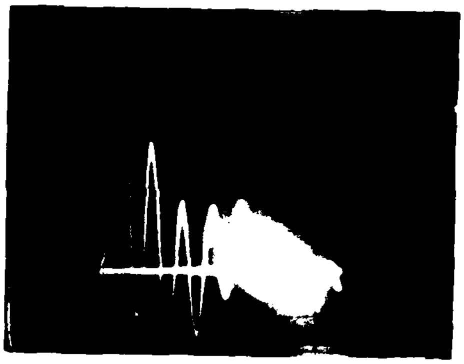


640 Amp/div 0.1 us/div

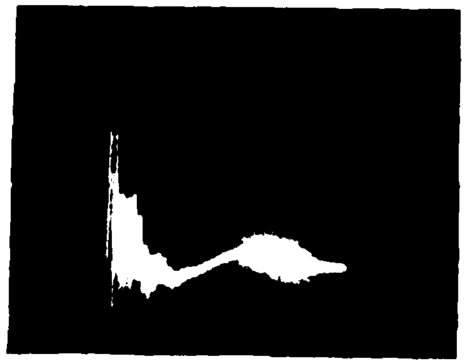


640 Amp/div 0.4 us/div

E-FIELD

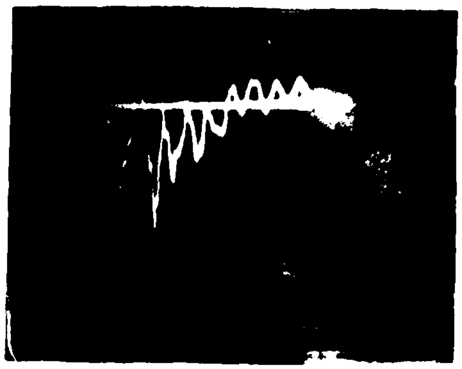


80 kV/m/div 0.4 us/div

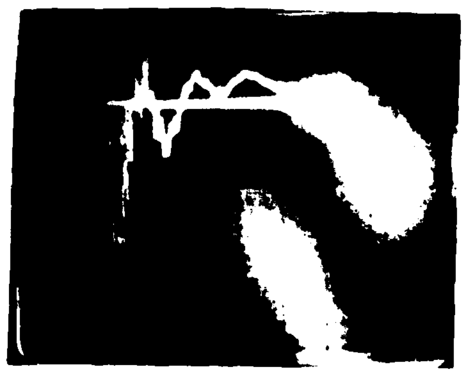


80 kV/m/div 2.0 us/div

H-FIELD



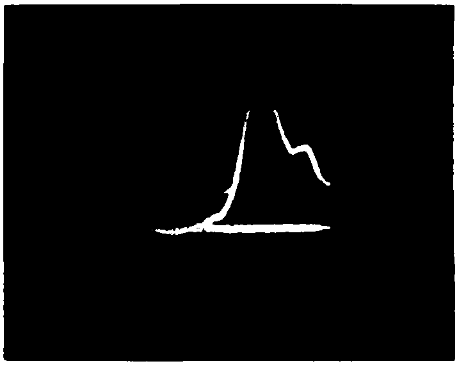
70 A/m/div 0.2 us/div



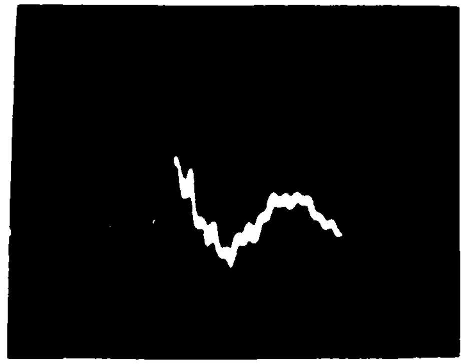
35 A/m/div 1 us/div

Figure 5c. Oscillograms of Cylinder With Rear Spark Gap

OPEN CIRCUIT VOLTAGE ON 25 FOOT WIRE ,10 INCHES INSIDE A ONE FOOT APERTURE NEAR CENTER OF CYLINDER

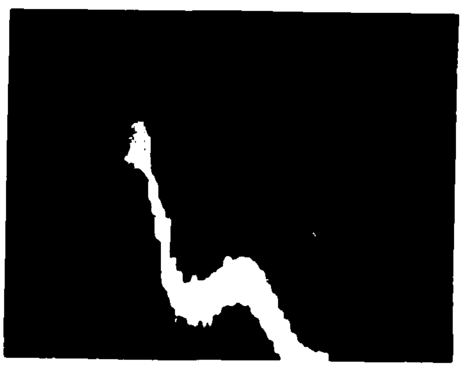


4 V/div 0.1 us/div

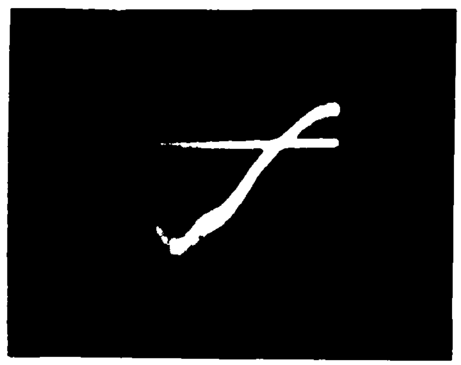


4 V/div 0.4 us/div

SHORT CIRCUIT CURRENT ON WIRE



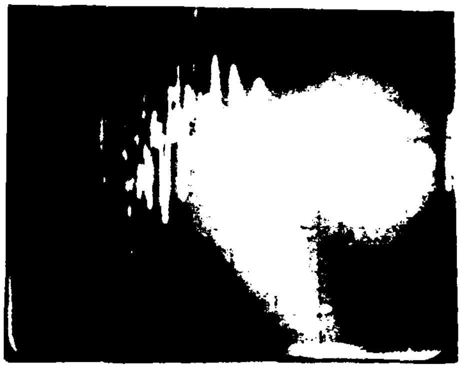
0.2 A/div 0.4 us/div



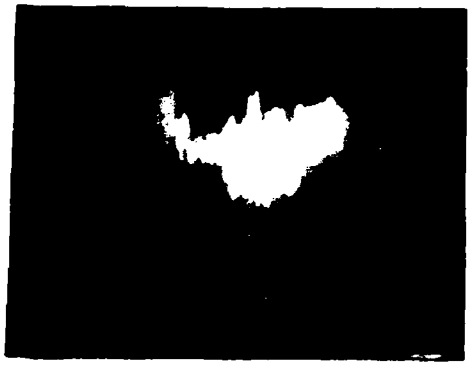
0.4 A/div 0.1 us/div

Figure 5d. Oscillograms of Response on Inside of Cylinder with NEMP Type Generator Feeding System

OPEN CIRCUIT VOLTAGE ON WIRE INSIDE CYLINDER

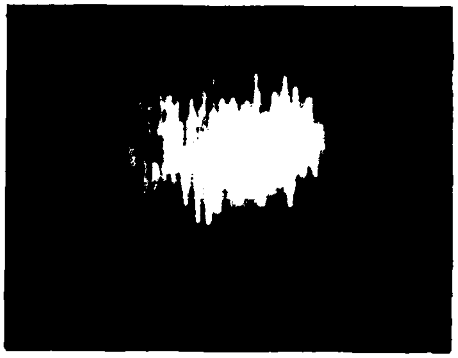


0.2 V/div   0.1 us/div

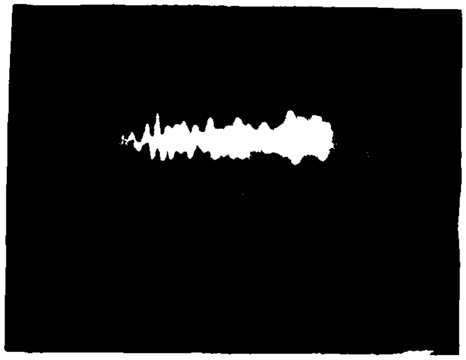


0.1 V/div   0.2 us/div

SHORT CIRCUIT CURRENT ON WIRE INSIDE CYLINDER



20 ma/div   0.1 us/div



80 ma/div   1 us/div

Figure 5e. Oscillograms of Response on Inside of Cylinder with NEMP Type Generator Firing into Ground Noise Tests

Marx generator into the array and measuring internal voltages on a wire antenna inside the cylinder and then short circuiting the Marx generator to ground, firing again, and again measuring the internal voltages. The ratio was approximately thirty-five to one or about 31 db difference. This suggests that the radiated noise from the Marx generator is approximately 31 dB down from the actual test currents and that this prescribes the basic signal noise limitations of the system for the end shielded Marx. The analytical investigations by EMA suggested that a simple vertical shield such as used in McDonnell-Douglas tests with their shock excitation system approach, would help substantially to improve the signal noise ratio of the system.

8.0 - Design of a Full Scale Test Arrangement

Next a design was carried out for a full scale test at approximately the four megavolt level of a full size aircraft, as shown in Figure 6a & 6b. An F-16 was selected as the test vehicle along with the Air Force Aeronautical Laboratories and the AFWAL large mobile Marx impulse source. On the basis of the cylinder studies which determined that simple peaking capacitors could be used, a single peaking capacitor stack was selected for this design utilizing energy storage capacitors stacked from between the outside of the coaxial test arrangement to the input center point to provide both input bushing rating and peaking capacitor fast rise currents.

The mechanical construction of this system is based on readily obtainable elements. These include telephone poles or fiber glass or metal aluminum street light standards guided by cables for supporting the wire grid around the vehicle. The wire grid would be both underneath and over the vehicle which would be supported on a simple timber stack. The EMP tests of the F-16 were at one point carried out by suspending the vehicle on a crane with insulated cables and this, of course, could be used for this purpose also.

Thus the basic design utilizes readily available components for the support towers and aluminum clothes line wire and laminated tresses for supporting the cables. The input spark gap and the downstream gap or termination resistors are both fabricated of fiber glass gasoline service station storage tanks. The tanks are approximately four by eight and permit the utilization of SF6 in order to improve the fast firing characteristics by shortening the gap and reduction of the gap inductance. Because of the high cost of SF6 and because of the fact that inductance is actually being added to the circuit, it is very possible that the system will work quite suitably with air at slightly over atmospheric pressure in lieu or in place of expensive SF6. This comment applies to both the input firing gap and the downstream gap used for E field excitation.

9.0 - CONCLUSIONS

The conclusions drawn from the tests were that the approach is

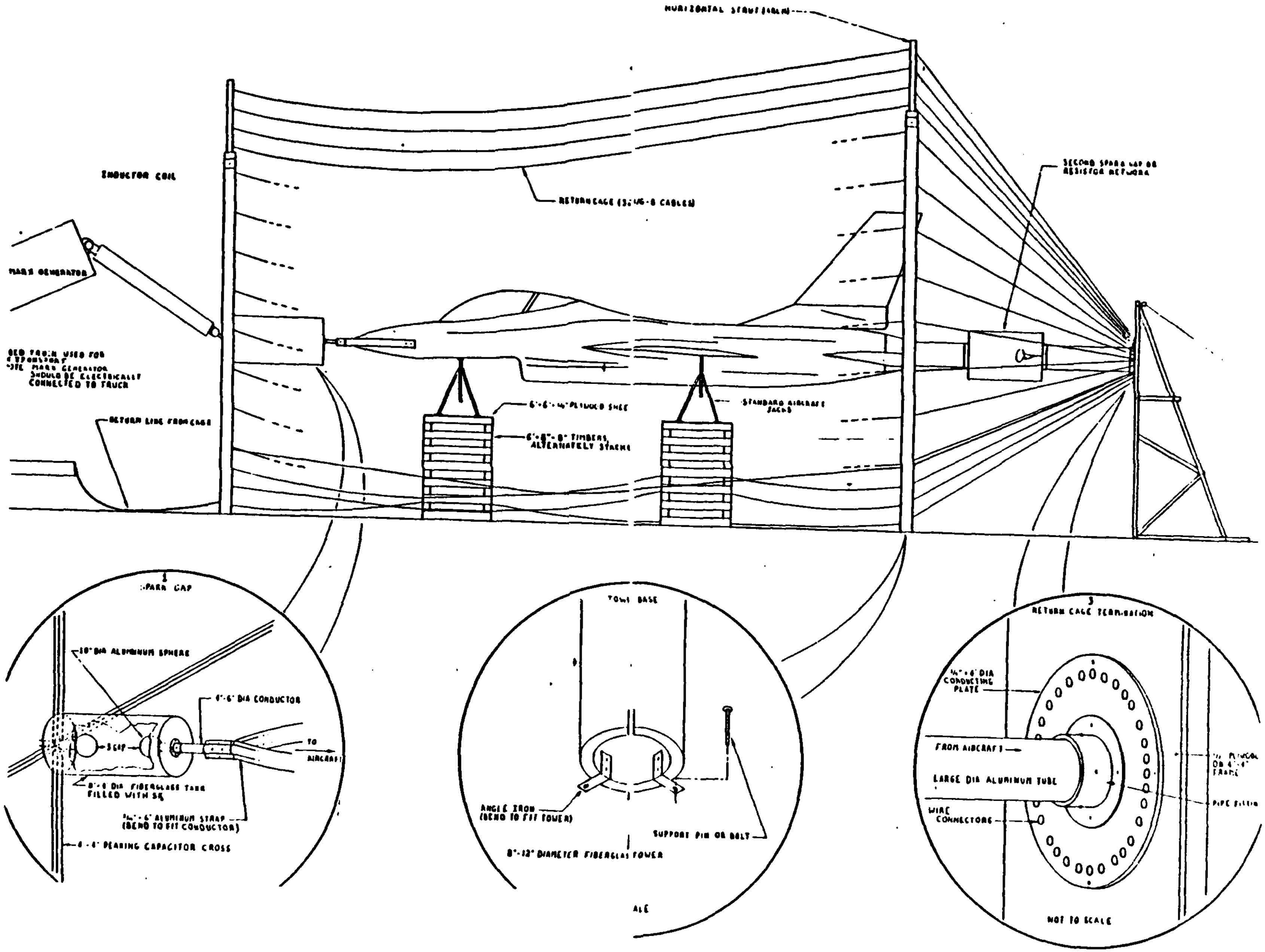


Figure 6a. Full Scale Test Arrangement.

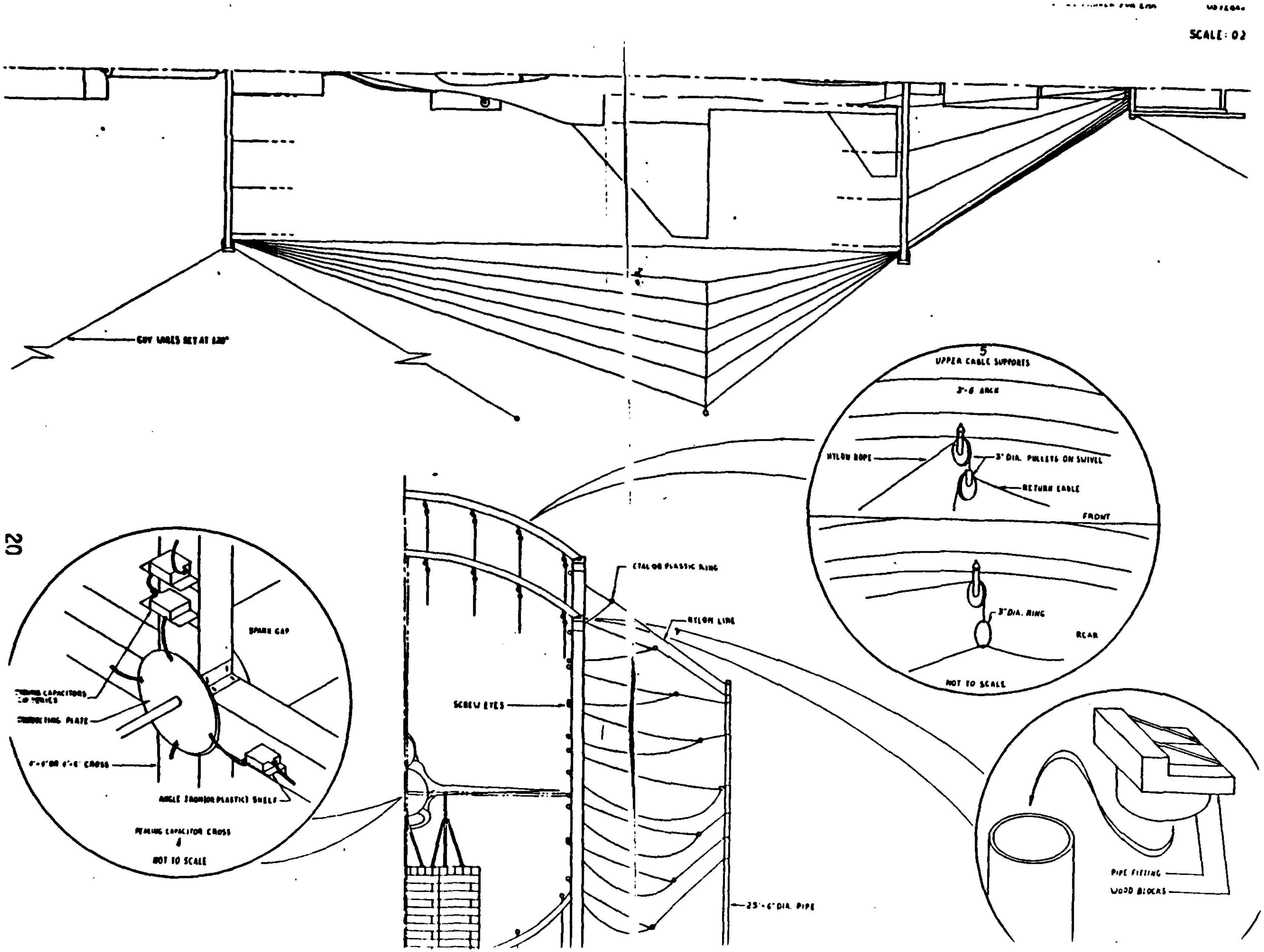


Figure 6b. Full Scale Test Arrangement.

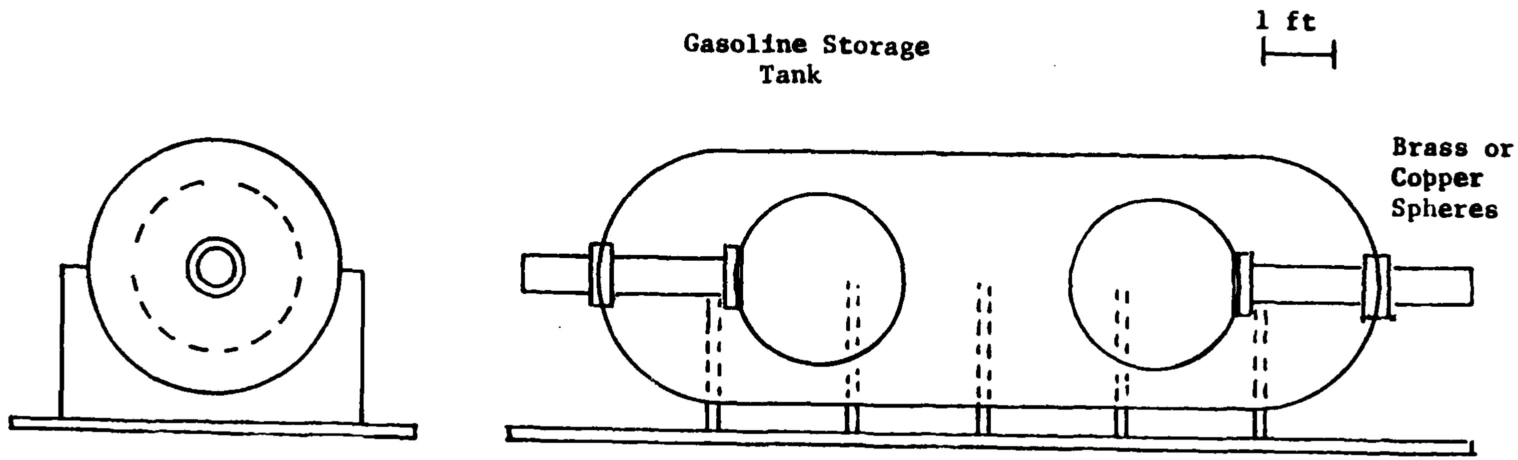


Figure 6c. Section View of Gasoline Storage Tank Spark Gap and/or Water Resistor. Fill With SF-6 for Spark Gap, Water Electrolyte for Termination Resistor.

feasible and provides a fast rising clean wave front of wave with a rise time which is an order of magnitude better than the previous system and could be obtained with low cost energy storage peaking capacitors.

10.0 - RECOMMENDATIONS

One element which is missing from the proposed test arrangement is the ability to supply the longer duration wavetail to induce the resistively coupled currents into the interiors of composite structures. A way which has been developed for accomplishing this is the use of a crowbar switch and this is recommended for further development under the program. A similar analytical study and brief experimental study would be carried out with the existing test arrangment to evaluate the effect of the crowbar circuits on the operation of the NEMP fast rise peaking system.

One obvious problem which the crowbar presents is that the crowbar is generally utilized for lower impedance circuits, however, the higher impedance circuits are necessary in order to obtain the rise time as the basic rise time is a function of L/Z, the system surge impedance. Thus the lower impedance crowbar system which would allow lower driving voltages were given current and much greater energy, might cause difficulties in the faster rise time. A continuation program is therefore recommended to investigate these additional parameters.

APPENDIX A
LIST OF MATERIALS
FOR
AFWAL NEMP TYPE LIGHTNING SIMULATOR

1.0 FEED INDUCTOR
(1) - 15 Feet long x 18" dia. plastic tube inductor with No. 6 wire wrapped with one foot spacing between turns. The inductor coil is to be mounted on one end to the capacitor cross conducting plate via a 90 deg. swivel pipe fitting. The other end of the inductor coil is to be mounted to the AFWL Marx Generator also employing a 90 deg. swivel pipe fitting to allow for vertical adjustments.

2.0 SPARK GAP
(1) - 8 Feet long x 4 Feet dia. fiberglass gasoline storage tank with (2) - 18" dia. brass spheres spaced 3 Feet apart in SF6. Each sphere is mounted on 4 - 6" dia. standard pipe conductor extending from within the storage tank and centered through each end of the tank. One end of the tanks conductor pipe is extended through and mounted to the peaking capacitor cross and Spark Gap tank and then mounted to the AFWL Marx Generator conducting plate using standard pipe fittings. The other end of the tanks conductor pipe will be mounted using standard pipe fittings and extend through the tank to the 1/16" x 6" Aluminum Aircraft Nose Strap cut to length to accomodate the aircrafts size, bent to fit and fastened to the conductor pipe.

3.0 HIGH ENERGY RESISTOR
(1) - 8 Feet x 4 Feet dia. fiberglass gasoline storage tank with (2) - 18" Dia. brass spheres spaced 3 feet apart in copper sulfate. Each sphere is mounted on 4 - 6" dia. standard pipe conducter and mounted to each end of the tank using standard fittings. (2) - 24" dia.,cut to fit aluminum tubes, extend from mounts at each end of the tank to the conducting plate and the tail end of the aircraft.

4.0 SUPPORT POLES
(4) - Wood telephone poles or fiberglass light poles, approximately 30 - 35 feet long or cut to required length with a 5 feet length variance for the 2 front and 2 back supports.

5.0 PEAKING CAPACITOR SUPPORT STRUCTURE
- Double 2"x 6" lumber (Permali or epoxy glass preferred to reduce flashover) transverse and vertical for support of peaking capacitors.

6.0 PEAKING CAPACITORS
- Standard energy storage capacitors to give desired peaking amplitude - nominal- 160 capacitors 10 nF at 100 KV

each. The peaking capacitors should be mounted in a spiral to allow the serial connected capacitors to fit in the alloted grid.

7.0 AIRCRAFT SUPPORT STRUCTURE

(3) columns of 33 Stacked 6' x 8" x 8" timbers, wood pegged for interlocking.
(4) - 6' x 6' x 1" Plywood sheets placed on top of the (3) timber columns for Aircraft Jack supports.
(3) - Standard Aircraft Jacks (insulated jacks preferred) mounted on top of the timber and plywood columns.

8.0 UPPER and LOWER SUPPORT BEAMS

(4) - Weyerhouser laminated wood or fiberglass beams. (2) beams are mounted on top of the front and back support poles and (2) are mounted at there base using beam attachment blocks. Attached to each beam are a series of 3" dia. swivaled pulleys threaded with nylon rope to form the test grid.

9.0 WIRE AND PULLEYS

- Aluminum clothsline wire and standard pulleys (no special requirements)

10.0 CROSS WIRING

- Aluminum clothsline wire for griding wires into six to nine foot squares.

11.0 TOP BEAM FITTING

- Special wood or plastic attachment blocks.

LIQUID AND GAS STORAGE TANKS

13p

ANK CO.

ebruary 1981

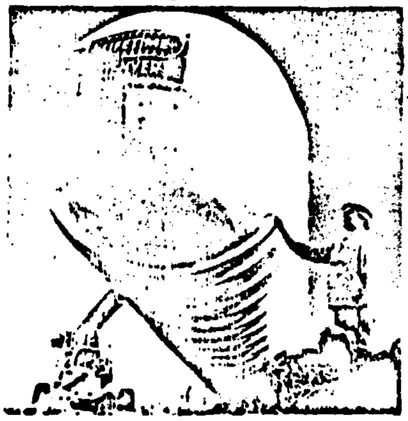
1. PRODUCT NAME

Lifetime Underground Storage Tanks

2. MANUFACTURER

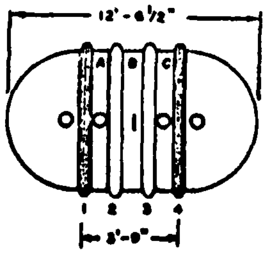
LIFETIME FIBERGLASS TANK CO.
5000 Packing House Road
Denver, CO 80216
Phone: (303) 623-0333

3. PRODUCT DESCRIPTION



Standard U.L. Tanks:

MODEL	ACTUAL CAPACITY (GALLONS)	DIMENSIONS (ALL 8' DIA.) (LENGTH)	NOMINAL WEIGHT (LBS.)	STANDARD NUMBER OF 4" FITTINGS INCLUDED IN PRICE OF TANKS
500	550	7'6" - 4' DIA.	200	4
1,000	1,010	12'8" - 4' DIA.	400	4
2,000	2,550	10'1"	800	4
4,000 D-1	3,380	12'6½"	1,084	4
4,000 D-2	4,380	15'6"	1,368	4
6,000 D-1	5,380	18'5½"	1,652	6
6,000 D-2	6,380	21'5"	1,936	6
8,000 D-1	7,380	24'4½"	2,220	6
8,000 D-2	8,380	27'4"	2,504	6
10,000 D-1	9,380	30'3½"	2,788	6
10,000 D-2	10,380	33'3"	3,072	6
12,000 D-1	11,380	36'2½"	3,356	6
12,000 D-2	12,380	39'2"	3,640	6
15,000	15,380	48'6"	4,492	6



3380 Gals.

☆U.S.Government Printing Office: 1984 — 759-062/823

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